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Thermal imaging and TC oximetry measurements of hyperbaric oxygen therapy (HBO) effects on trophic ulceration of the crura

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Abstract We performed studies on the influence of hyperbaric oxygen therapy on the trophic ulceration of the crus using thermal imaging and TC oximetry. Thermograms for two groups of volunteers, one suffering from trophic ulceration of the crus (11 patients aged 63.6 ± 15.2) and one healthy (6 people aged 42 ± 8), were completed before and after hyperbaric oxygenation. In addition, the oxygen tension in each patient's crus was measured. Hyperbaric oxygenation has an influence on biological as well as physiological processes that occur in the tissue. It is apparent that these processes may have an impact on the differentiation of tissue temperature. The studies showed some differences in skin temperature between research groups. A bigger differentiation of skin temperature was observed for patients who suffered from ulceration. It follows that there are statistically significant differences between the mean temperature for all chosen regions of interest obtained before ($p = 0.0003$) and after ($p = 0.03$) hyperbaric oxygen therapy. Moreover, the differences ($\Delta T = T_{\mathrm{meanAR01}} - T_{\mathrm{meanAR04}}$) between mean temperature characterization in chosen areas seem to be a little smaller. We observed that this difference changed from $\Delta T = 3.3$ °C, estimated before hyperbaric oxygenation, to 2.5 °C, obtained after hyperbaric oxygenation, which may suggest improvement in the thermoregulation process. A similar situation was observed for the healthy group, but the temperature changes were smaller. The changes of the mean temperature may be correlated to some changes in wound cellular metabolism and the increase of microcirculation due to neoangiogenesis as well as the improvement of thermoregulation in the ulceration due to a rebuilding of the right cellular matrix. In addition, we observed that the mean values of oxygen pressure in the tissues (TCPO2) increased from 22 to 39 mmHg after hyperbaric oxygenation for patients with ulceration in their lower extremities. We also detected that oxygen pressure measurements and infrared imaging seem to be useful in the qualitative analysis of hyperbaric oxygenation treatment, and may offer some useful information about the hyperbaric oxygen therapy effects in trophic ulceration.

Keywords Thermal imaging · TC oximetry · Hyperbaric oxygen therapy (HBO) · Ulceration of the crus

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Introduction

We know that thermal analysis may be useful in medical diagnostics, i.e., thermal analysis of human serum or soft tissues [1, 2], and in other applications where a temperature map can offer additional information [3]. Thermal imaging was also used as a diagnostic tool for patients with spine diseases who were treated by whole body cryotherapy [4]. However, there are only a few papers concerning the application of thermography in hyperbaric oxygen therapy [5, 6].

This article covers the diagnostic value of thermovision in hyperbaric oxygen therapy (HBO) which has been developed significantly over the last century.

In hyperbaric oxygen therapy, the whole human body is exposed to increased atmospheric pressure in a special room called a hyperbaric chamber. There are two predominant types of hyperbaric chambers: a single patient chamber, inside which 100% oxygen is normally used, and a multiple patient chamber (holds up to eight patients), generally with an attendant who monitors the patients and assists with the operation of equipment and with emergency situations. Inside these types of hyperbaric chambers, the patients are subjected to air under 2.5 ATA and they are simultaneously inhaling 100% oxygen through a mask or helmet. The therapy usually takes 86 min [7–9].

Hyperbaric oxygen therapy is based on the "ideal gas" laws of physics. According to Boyle's law, an increase of air pressure causes a decrease of gas bubble volume (i.e., soluble in the blood of the veins). This phenomenon can have an application in the embolic phenomena, such as in decompression sickness. However, the most important law that has an application in hyperbaric oxygen therapy is Henry's law. Henry's law determines the proportion of the amount of gas dissolved in the liquid in relation to the partial pressure of the gas exerted on the surface of the liquid. This signifies that the increase of atmospheric pressure in the chamber leads to the increase of oxygen dissolved into the plasma. The delivery of oxygen through the skin caused by tissue hydration is also regulated by Henry's law [7, 8].

The value of hyperbaric oxygenation has been proven, and it is widely used for hypoxic and ischemic wounds where a marked decrease of oxygen pressure can be observed in tissues [9]. The most important advantage of hyperbaric oxygen therapy is realized in tissues suffering from a lack of oxygen due to damage in the vasculature. Multiple components of the wound healing process are affected by oxygen concentration or gradients. Angiogenesis occurs in response to high oxygen concentration, which explains why hyperbaric oxygen therapy can be an effective therapy to treat such diseases. Fibroblast proliferation as well as collagen synthesis is oxygen dependent. It is known that collagen is the foundational matrix for angiogenesis, and HBO stimulates growth factors involving angiogenesis and other mediators of the wound healing process. It is thought that the hyperbaric oxygenation influences the skin and mucous membrane resulting from subcells, cells, and tissue reactions. The related effect is the increase in the oxygen transport capacity of blood, which enhances the tissue proliferation processes [7–13]. During the wound healing process, the increased oxygen pressure effects ischemic soft tissues by improving the preservation of energy metabolism and reducing swelling; these factors improve the microcirculation and blood supply to the ulceration [7–9]. However, the most important effects of hyperbaric oxygenation are the stimulation of fibroblast proliferation and differentiation, increased collagen synthesis, improved neovascularization, and destruction of different kinds of bacteria by leukocytes [9]. It is understood that every treatment which increases oxygen supply to the tissues or avoids hypoperfusion of the wound leads to a shortening of healing time and a decreased susceptibility to infection [9]. Such processes may also be connected with changes in the inflammation areas, and also may have some influence on the thermal skin map. In the hyperoxic environment tissues consume a larger amount of glucose [14, 15]. Cells in the surroundings of the capillaries consume glucose so extensively that the supply to the most peripheral cells is limited. Such a differentiation of glucose consumption seems to have an influence on the peripheral of wound metabolism and also on thermal behavior. Moreover, during the healing process, new blood vessels grow rapidly from areas of high oxygen tension and low lactate concentration, to areas of low oxygen tension and high lactate concentration, where they may also have some influence on thermal tissue differentiation and temperature gradient changes around the wound [9]. The differentiation of skin temperature may be seen particularly between internal and peripheral parts of the wound where new blood vessels start growing.

All these processes connected with HBO treatment such as neoangiogenesis, synthesis of collagen, and antibacterial reaction may be connected with the change of metabolism and can have an influence on tissue temperature change [6, 16].

The HBO is applied to many cases of respiratory and circulatory diseases as well as to cases of poisoning, such as carbon monoxide and cyanide poisoning, during radiation and in different, non-healing wounds. The example of non-healing wounds is found in the trophic ulceration of the crus. This kind of disease is difficult to cure and is severely harmful. Consequently, it is reported that almost 37% of people are afflicted with *venous insufficiency* which can cause *varicose veins* and lead to *trophic ulceration* [7, 8]. The healing process can last up to several years.

Thermal imaging as a noninvasive method has various applications in medicine that include breast thermography, vascular diseases, dermatological diseases, studies of inflammatory response, Raynaud phenomenon, foot ulceration among patients with diabetes mellitus and low back pain diseases [17–23]. Furthermore, it has been reported that thermovision was used in physiological measurements with standard radiographic investigations [24, 25]. The disadvantage of thermal imaging is its poor specificity. Thermal imaging cannot identify the increased cutaneous perfusion. The presence of inflammatory effects, in both deep and superficial vessels, can be misleading when using thermal imaging alone [24]. However, thermal measurements are very easy to perform and can give some important information connected with blood supply and metabolism [17, 18, 24]. Blood vessels close to the skin surface can be easily traced with thermal imaging [25] that is sensitive to warmth from blood vessels [24, 26]. In some diseases, such as diabetes, the increase of blood flow to the feet was studied using different techniques [27, 28]. The basics of thermal imaging of skin thermal changes as a result of different physical factors have been reported in medical literature [17, 18, 24, 26, 29].

Currently, only the TCPO2 measurement is used to study the hyperbaric oxygenation therapy effects, and the measurement is usually performed before and after a hyperbaric oxygenation session to check the changes of oxygen pressure in the tissues. Taking into account different biological and physiological processes mobilized and started in the hyperoxic environment, and their possible meaning for tissue temperature, the authors tried to find another noninvasive diagnostic technique that is able to give additional information connected with the rebuilding of tissue and metabolism changes inside and around the ulceration.

Experimental procedures

The studies were performed for two independent groups consisting of 11 (9 female and 2 male) patients aged 63.6 ± 15.2 suffering from *trophic ulceration* (who were subjected to 5–15 hyperbaric oxygen therapies) and 6 healthy people (6 females) aged 42 ± 8. Both legs were measured before and after each session. The investigations were carried out at the Burn Treatment Center in Siemianowice, (Silesia) Poland where a multi-patient hyperbaric chamber was installed. Each session of hyperbaric oxygen therapy lasted 86 min. The air pressure in the chamber was 2.5 ATA. The bandages were applied between each session of hyperbaric oxygenation. They were loosely applied to prevent pressure in the crus. In addition, before and after each hyperbaric oxygen therapy the crura were uncovered to stabilize the temperature between the tissue and surrounding area. The same procedure was used for all patients during the preparation for examination.

The distribution of the skin surface temperature was monitored using a Thermovision Camera A40M calibrated by a black body. The sensitivity of the thermovision camera was 0.07 K. The thermograms of chosen regions of interest (areas around the wound and for the healthy subjects in corresponding areas excluding the wound—AR_i where $i = 1, 2\ldots$) were performed before and immediately after HBO in a special room outside the chamber according to the standards of thermal imaging in medicine [29].

Temperature in the chamber and in the measurement room during therapy was 22.5 ± 1 °C. Statistical analysis were done in Statistica 7.1 using *t* tests, Wilcoxon's, Leven's, and ANOVA tests. Differences with $p < 0.05$ were regarded as significant (where p is the level of statistical significance).

TCPO2 oximetry parameters were measured by a TCM400 made by TINA with Clark's probes E5250. The probes were put above the ulceration—closer part, below—farther and on the foot (Fig. 1). The accuracy of a TCPO2 measurement is 2 mmHg.

Results and discussion

The thermograms with temperature parameters (minimum temperature—T_{min}, maximum temperature—T_{max}, and average temperature—T_{avg}) derived from chosen areas of the crus were performed before (a) and after (b) the hyperbaric oxygenation session for a representative patient suffering from *trophic ulceration* of the crus and for a healthy one are presented in Figs. 1 and 2, respectively.

The chosen areas of the crus are: AR01—closer area above the wound (area measured from 3 to 5 cm below the knee-cap up to the middle of the crus), AR02—ulceration, AR03—farther area below the wound (area measured from the middle of the crus, without the ulceration, up to 3–5 cm above the ankle), and AR04—foot surface (area below the ankle about 5–7 cm long—included the TCPO2 measurement point). There was no wound area for the healthy person—AR02 (Fig. 2).

It follows from the thermograms and collected temperature parameters that, clearly, the body skin surface temperature decreased after HBO for the healthy people as well as for patients with an ulceration of the crus. In general, a bigger decrease of the mean temperature due to HBO is observed for the affected patients and not for the healthy ones. A bigger differentiation on the skin temperature map was observed for patients with an ulceration because of hyperbaric oxygen therapy.

Hyperbaric oxygen therapy increases oxygen supply to the ulceration and other wounded tissues which improves the rate of healing process and decreases susceptibility to infection [9]. Such processes can also cause changes to inflammation areas which should be connected with the thermal skin map changes.

For a better view of the changes to the temperature parameters, statistical outlines were performed. Statistical analysis confirmed a significant decrease ($p < 0.05$) in the mean temperature as a result of HBO. The changes to the mean temperature obtained from chosen areas for all patients were performed before (a) and after (b) HBO are presented in Fig. 3.

One can observe some disturbance of the mean temperature in the selected areas when it is considered along

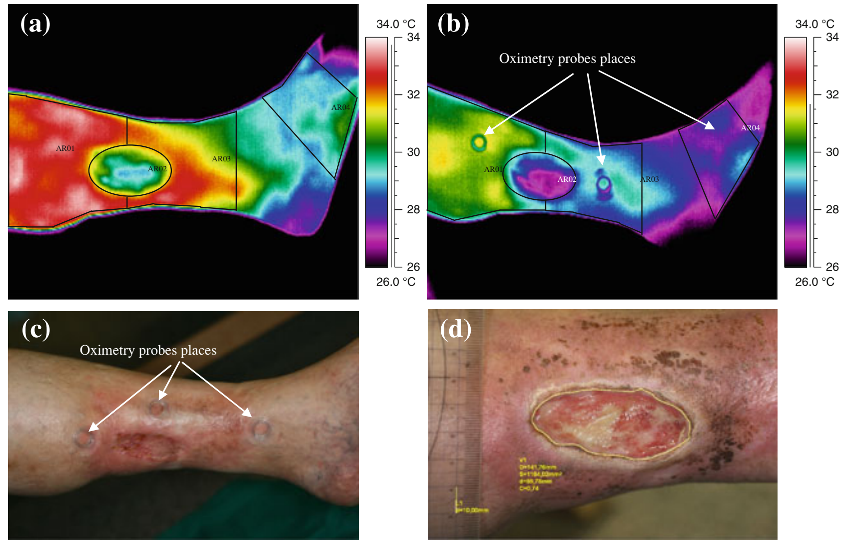

Fig. 1 The representative thermal images and results of temperature parameters from the chosen areas (AR01–AR04) were performed before (**a**) and after (**b**) the HBO session, digital pictures of the crus (**c**) and a close-up of the wound (**d**) for a representative patient suffering from *trophic ulceration* are presented

Before HBO	T_{Min} /°C	T_{Max} /°C	T_{Avg} /°C
AR01	31.6	34.0	33.0
AR02	28.8	32.0	30.2
AR03	28.1	33.4	31.5
AR04	25.0	31.0	28.9

After HBO	T_{Min} /°C	T_{Max} /°C	T_{Avg} /°C
AR01	28.7	31.7	30.6
AR02	26.6	29.5	27.7
AR03	27.1	30.1	28.9
AR04	26.4	29.2	27.7

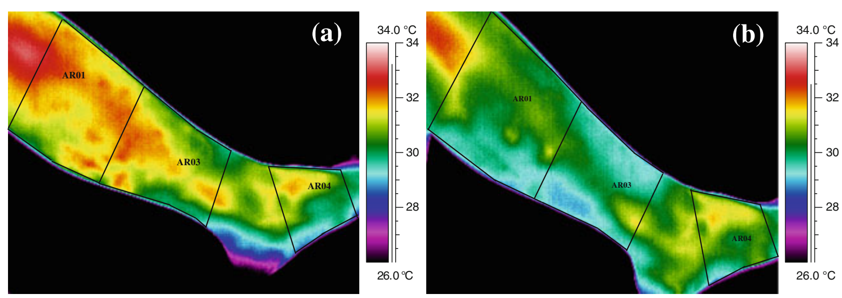

Fig. 2 The representative thermal images and results of the temperature parameters from the chosen areas for a representative healthy person, performed before (**a**) and after (**b**) the HBO session

Before HBO	T_{Min} /°C	T_{Max} /°C	T_{Avg} /°C
AR01	29.8	33.3	31.7
AR03	28.9	32.3	31.1
AR04	28.2	31.8	30.2

After HBO	T_{Min} /°C	T_{Max} /°C	T_{Avg} /°C
AR01	28.9	32.0	30.3
AR03	28.8	31.7	29.9
AR04	28.0	31.6	30.5

the crus from the closer to farther parts, especially the decrease in the mean temperature in the wound area (AR02), should be noted. The healing process induced by hyperbaric oxygenation improves neoangiogenesis, especially around the periphery of the wound. It was reported that new blood vessels grow rapidly from areas of high oxygen tension and low lactate concentration to areas of low oxygen tension and high lactate concentration [9]. This suggests that such processes may have influence on cells and tissue metabolism changes around the wound. Moreover, hyperbaric oxygenation has an effect on the stimulation of fibroblasts, collagen synthesis, and neovascularization, which may also have an impact on tissue temperature changes. However, the temperature should be dependent on changes in the inflammatory state around the wound, which plays an important role in killing different kinds of bacteria with leukocytes, which are also stimulated by hyperbaric oxygenation [9, 14, 15]. Furthermore, the temperature changes may be connected with the reduction of swelling around the wound where it causes an increase in metabolism due to a narrowing of the capillaries and a reduction of the blood supply to the ulceration. As a result,

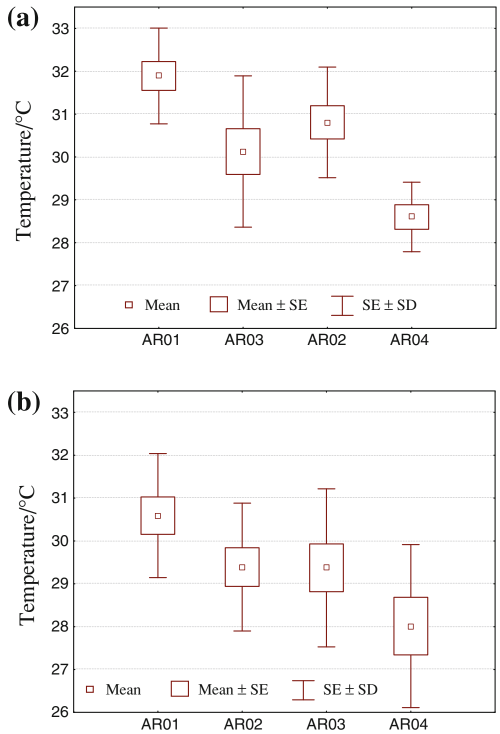

Fig. 3 The changes to T_{mean}, obtained from chosen areas marked in Fig. 2 for the study group, were performed before (**a**) and after (**b**) HBO. Statistical values used: mean, SE, SD mean, respectively, mean value of oxygen pressure, standard error, and standard deviation

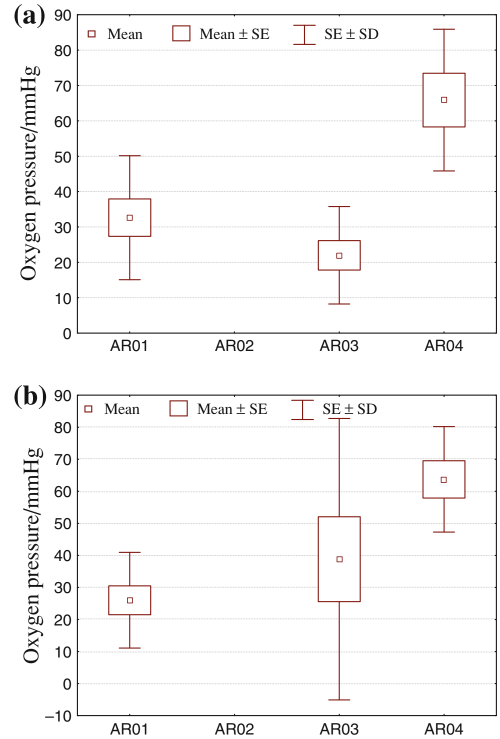

Fig. 4 The changes to the oximetry parameters obtained from chosen areas exhibited in Fig. 2 for the study group were performed before (**a**) and after (**b**) HBO. It should be noted that the oximetry probes were not placed inside the ulceration, so in the TCPO2 measurements AR02 was not marked. Statistical values used: mean, SE, SD mean, respectively, mean value of oxygen pressure, standard error, and standard deviation

the decreased temperature around the wound observed after hyperbaric oxygenation may give some information about the improvement or changes in blood supply, and may be connected with some of the healing processes.

These processes may have some reflection on the thermal skin map. It is clearly apparent in Figs. 1a, b and 3 that a higher temperature is observed around (above and below) the ulceration, in what may be connected to an inflammatory state, and swelling changes around the ulceration—AR02. After hyperbaric oxygenation, the temperature changes become more monotonic.

Studies performed showed statistically significant differences between mean temperature values for all chosen areas obtained before ($p = 0.0003$) and after ($p = 0.03$) hyperbaric oxygen therapy session. In addition, the difference ΔT obtained between mean temperature characterization of all regions of interest ($\Delta T = T_{meanAR01} - T_{meanAR04}$) became a little smaller. The temperature analysis showed that ΔT changed from $\Delta T = 3.3$ °C, before HBO, to 2.5 °C, obtained after hyperbaric oxygenation. The changes of temperature differences in chosen areas may suggest some influence of hyperbaric oxygenation on the thermoregulation process in tissues. A similar decrease of ΔT was observed for the healthy group; however, the values captured were smaller.

The changes of the mean temperature may be correlated with metabolism and an increase of blood flow and microcirculation as a result of hyperbaric oxygenation. They seem to confirm that hyperbaric oxygenation leads to neoangiogenesis and healing processes, including the improvement of thermoregulation in the ulceration due to the regeneration of the right cellular matrix and the increase of microcirculation [7–9].

In the case of the ulceration of the crus, oxygen tension measurements can give valuable information. Therefore, oximetry parameters procured from chosen areas for the group of patients performed before (a) and after (b) HBO were determined and presented in Fig. 4.

Statistical analysis showed significant changes in the oximetry parameters between all examined areas AR01, AR03, and AR04 performed before HBO ($p < 0{,}001$). One can see an essential decay of oxygenation in area AR03 below the wound which disappears after the hyperbaric oxygenation session. The changes to of oxygen pressure become monotonic ($p = 0.06$). The mean increase of this parameter was measured from 22 mmHg before to 39 mmHg after hyperbaric oxygenation. The analysis of

TC oximetry parameters after HBO point to an increase in the oxygen level in the area below the ulceration. It may have a potential therapeutic impact because it is connected with the oxygen transport to further parts of the ulceration tissues. A very important physical process is the dissolving of oxygen in blood fluids due to a forcing of oxygen to the soft tissues through the skin. Increased oxygen pressure in the wound can lead to a reduction of swelling, increasing the leakage of fluid through the damaged blood vessels that helps the oxygen to get to the damaged tissue area and improves the healing of the wound. It also stimulates the activity of the cells, creating the fibers that are normally the basis of new healthy tissue. The mechanisms stimulated by hyperbaric oxygen therapy in the tissue, both on the cell and subcell levels, can lead to *neoangiogenesis* and improve the blood supply and as a result temperature changes due to the improvement of heat exchange, mainly by convection, which takes place within the blood supply. In addition, in higher oxygen pressure, as opposed to a normal atmospheric conditions, oxygen exerts a toxic activity on bacteria (aerobic as well as anaerobic). This phenomenon is called as the "oxygen explosion". All these processes contribute to a rebuilding of the extracellular matrix and reduce the time of therapy [7–10].

The infrared imaging as well as TC oximetry detects disorders in the vicinity of the ulceration. Both techniques show that after HBO, observed changes become smaller and more regular. However, some articles showed that the therapeutic effects of HBO can depend to a large extent on the age of the patient and the presence of diseases [30]. The problem is complicated and requires further studies.

Conclusions

It follows from our studies that oxygen pressure measurements and infrared imaging may give some useful information about physiological and therapeutic effects of hyperbaric oxygen therapy in trophic ulceration of the crura.

Temperature differentiation observed around non-healing wounds seem to be a little smaller after hyperbaric oxygenation, which may suggest that the improving thermoregulation processes around the wound is due to the rearranging microcirculation.

However, the study group was small and what was learned should be treated only as preliminary results.

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